Effect of Land-Cover Change on Terrestrial Carbon Dynamics in the Southern United States

Hua Chen, Hanqin Tian,* Mingliang Liu, Jerry Melillo, Shufen Pan, and Chi Zhang

ABSTRACT

Land-cover change has significant influence on carbon storage and fluxes in terrestrial ecosystems. The southern United States is thought to be the largest carbon sink across the conterminous United States. However, the spatial and temporary variability of carbon storage and fluxes due to land-cover change in the southern United States remains unclear. In this study, we first reconstructed the annual data set of land-cover of the southern United States from 1860 to 2003 with a spatial resolution of 8 km. Then we used a spatially explicit process-based biogeochemical model (Terrestrial Ecosystem Model [TEM] 4.3) to simulate the effects of cropland expansion and forest regrowth on the carbon dynamics in this region. The pattern of land-cover change in the southern United States was primarily driven by the change of cropland, including cropland expansion and forest regrowth on abandoned cropland. The TEM simulation estimated that total carbon storage in the southern United States in 1860 was 36.8 Pg C, which likely was overestimated, including 10.8 Pg C in the southeast and 26 Pg C in the south-central. During 1860–2003, a total of 9.4 Pg C, including 6.5 Pg C of vegetation and 2.9 Pg C of soil C pool, was released to the atmosphere in the southern United States. The net carbon flux due to cropland expansion and forest regrowth on abandoned cropland was approximately zero in the entire southern region between 1980 and 2003. The temporal and spatial variability of regional net carbon exchange was influenced by land-cover pattern, especially the distribution of cropland. The land-use analysis in this study is incomplete and preliminary. Finally, the limitations, improvements, and future research needs of this study were discussed.

The terrestrial ecosystems in North America have been suggested as a major carbon sink (Fan et al., 1998; Pacala et al., 2001). Land-use changes such as cropland establishment and cultivation, cropland abandonment, and subsequently forest regrowth are the primary mechanisms for transferring carbon between the land and the atmosphere (Houghton et al., 1999; Caspersen et al., 2000; Pacala et al., 2001; Tian et al., 2003; Birdsey and Lewis, 2003). Based on the Forest Inventory and Analysis (FIA) biomass data from late 1970s to the early 1990s, Pacala et al. (2001) estimated a carbon sink of between 0.30 and 0.58 Pg C yr^{-1} in the conterminous United States and about half of this sink was due to the forest regrowth on abandoned cropland. Using FIA data of five eastern states, Caspersen et al. (2000) showed that land-use change is the dominant factor contributing carbon accumulation in the eastern United States. Houghton et al. (1999) estimated an annual accumulation of 0.037 Pg C in the United States because of the land-use change in the 1980s, and the forest regrowth has taken up 0.280 Pg C each year during the same period using a bookkeeping model.

The southern United States covers about 215.6 million ha of land in 13 states from the Mid-Atlantic coast west to Texas and Oklahoma, representing approximately 24% of the land area, 60% of the forest land, and 25% of the agricultural land for the entire United States. This region has undergone a long-term transition from agricultural land use to secondary forests (Wear, 2002). Three major periods characterize land-use change in the southern United States: (i) the era of agricultural exploitation, (ii) the era of timber exploitation, and (iii) the era of recovery and renewal (Wear, 2002). Agricultural exploitation started in the 17th century but reached its peak in the late 19th century, when a vast cotton industry stretched from the Atlantic to Texas. Timber exploitation peaked in the first part of the 20th century. By the Great Depression, intensive agriculture and timbering had seriously degraded the land. Cropland was abandoned, and forests were reestablished and renewed over the next 40 yr (Wear, 2002). However, how the historical land-cover change influenced carbon storage and fluxes in the southern United States remains unclear, although Turner et al. (1995) suggested that the southern United States had the strongest biological carbon sink in the United States due to the young forest age structure in this region.

Traditionally, studies on effects of land-cover change on carbon dynamics have primarily depended on the FIA data and other land-cover inventory data sets (Turner et al., 1995; Brown and Schroeder, 1999; Houghton et al., 1983, 1999; Caspersen et al., 2000; Houghton and Hackler 2000a, 2000b; Pacala et al., 2001; Birdsey and Lewis, 2003). However, the FIA program started about 1930 and the field inventory was conducted only once every 10 yr until the late 1990s. The land-use history in the southern United States is much longer than the FIA data history. Data availability becomes an issue to examine the effects of long-term historical land-cover change on carbon dynamics. Even in the available FIA data, the estimate and extrapolation of belowground biomass and dead wood biomass still needs to be addressed adequately (Brown, 2002). Moreover, in most cases, the studies using FIA data could only provide the average values of carbon storage and fluxes for certain regions and time periods. As spatial and temporary variability of carbon dynamics is increasingly important

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Published in J. Environ. Qual. 35:1533–1547 (2006).
Special Submissions
doi:10.2134/jeq2005.0198

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Abbreviations: FIA, Forest Inventory and Analysis; NCE, net carbon exchange; SC, south-central region; SE, southeast region; TEM, Terrestrial Ecosystem Model.

to understand with respect to the mechanisms responsible for regional carbon dynamics (Schimel et al., 2000; Tian et al., 2003), it remains unclear how the spatial and temporal variability of carbon storage and fluxes resulting from the land-cover change in the southern United States changes over time. Spatial and temporal variability of carbon dynamics in terrestrial ecosystems could be well simulated at local, regional, and global scales using process-based spatially explicit biogeochemical models. Terrestrial Ecosystem Model (TEM), a process-based biogeochemical model, has been used to examine the effects of land-cover change on carbon dynamics in several studies (McGuire et al., 2001; Tian et al., 1999, 2003; Zhang et al., 2006). McGuire et al. (2001) compared four process-based ecosystem models, including TEM, to examine the effects of land-cover change as well as the effects of increasing CO_2 concentration and climate variability on global terrestrial carbon storage between 1920 and 1992. Tian et al. (2003) simulated the effects of land-cover change, climate variability, and increasing atmospheric CO_2 concentration on the regional carbon dynamics in monsoon Asia with a spatial resolution of one-half degree.

The objectives of this study were to examine (i) how land-cover change, in particular clearing for cropland, crop cultivation and harvest, and cropland abandonment and subsequent forest regrowth, influenced carbon storage and fluxes in the southern United States from 1860 to 2003 and (ii) how carbon storage and fluxes resulting from the land-cover change varied spatially and temporally during the period examined. In spatial scales, we focused carbon dynamic analysis on the two subregions—southeast and south-central—in the southern United States. In temporal scales, we concentrated the analysis in two periods—1860–2003 and 1981–2003. In this study, we first reconstructed the annual time series data set of land-cover of the southern United States from 1860–2003 with a spatial resolution of 8 km. Then we used a spatially explicit process-based biogeochemical model (TEM 4.3) to simulate the effects of land-cover change on the carbon dynamics in this region.

MATERIALS AND METHODS

Study Region

The southern United States region extends roughly from 75° to 100° west longitude and from 30° to 37° north latitude, including the southeast (SE) and south-central (SC) subregion. The SE covers Florida, Georgia, North Carolina, South Carolina, and Virginia while the SC includes Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Oklahoma, Tennessee, and Texas. The SE and SC cover approximately 28 and 72% of the southern United States, respectively. Elevations within the region range from near sea level along the Gulf and Atlantic coasts to more than 1800 m in the Appalachian Mountains. Overall, the climate is temperate, becoming largely subtropical near the coast. Summers are long, hot, and humid, with little day-to-day temperature change. Late June to mid-August receive local afternoon thundershowers. The coldest months are December, January, and February. Severely cold weather seldom occurs (Cooter, 1992). The dominant forest types in this region include temperate coniferous forest, temperate deciduous forest, and temperate mixed forest. There is some patchy distribution of tropical evergreen forest and tropical deciduous forest in the Gulf coastal states. The southern region produces over 50% of commercial timber harvests for the nation (Mickler et al., 2002). Most timber harvests occur in forest plantations with intensive forest management including site preparation, utilization of pesticides and fertilization, and rotation (Siry, 2002). Fire is another major disturbance in this region. Use of prescribed fire is an important forest management activity in the southeastern United States (approximately 2 million ha burned per year) (Mickler et al., 2002). Fire is used to remove logging slash before plantation establishment, reduce hardwood and herbaceous competition in young stands, improve wildlife habitat, and minimize catastrophic wildfire hazard in older stands.

Model Overview

The TEM is a process-based biogeochemistry model that was originally designed to simulate the dynamics of carbon and nitrogen in natural terrestrial ecosystems at continental to global scales (Raich et al., 1991; Melillo et al., 1993; McGuire et al., 1997; Tian et al., 1998, 1999, 2000). Due to the increasing importance of land-use change on carbon dynamics, TEM 4.2 incorporated the ideas of the Terrestrial Carbon Model (TCM) of Houghton et al. (1983) to track carbon fluxes generated from conversion of natural ecosystems to cultivation, including the fate of carbon in products (McGuire et al., 2001; Tian et al., 2003). The products are placed into three pools with residence times of 1, 10, and 100 yr, respectively. Unlike Houghton et al. (1983), however, changes in carbon storage are influenced by the relative rates of net primary production (NPP) and heterotrophic respiration (R_H) and the effects of environmental conditions on these fluxes. In addition, the model estimates of the initial carbon storage in vegetation and soils before disturbance are also influenced by spatial and temporal variations in environmental conditions. TEM 4.2 is able to simulate changes in carbon storage during three stages of disturbance: (i) conversion from natural vegetation to cultivation, (ii) production and harvest on cultivated land, and (iii) forest regrowth on abandoned cropland (Tian et al., 2003). The annual net carbon exchange (NCE) of the terrestrial biosphere with the atmosphere can be described by the equation:

$$\mathrm{NCE} = \mathrm{NPP} - R_H - E_{NAD} - E_{AD} - \mathrm{Ep} \qquad [1]$$

where NPP is net primary production, R_H is heterotrophic respiration, E_{NAD} represents emissions associated with nonanthropogenic disturbance (e.g., wildfires, insect infestations), and E_{AD} represents emissions from anthropogenic disturbance such as cropland conversion from forests. In Eq. [1], E_{AD} is expressed as the conversion flux (e.g., the burning of slash and fuelwood). The term Ep represents the decomposition of products harvested from ecosystems for use by humans and associated livestock. In this study, we will not consider E_{NAD} due to the lack of the spatial data of wildfires and insect infestations. Thus, the NCE equation can be described by the equation:

$$\mathrm{NCE} = \mathrm{NPP} - R_H - E_{AD} - \mathrm{Ep} \qquad [2]$$

A negative NCE value indicates that terrestrial ecosystems are carbon sources to the atmosphere, whereas a positive NCE value means a terrestrial carbon sink. The details of how TEM 4.2 simulates these processes are referenced in McGuire et al. (2001) and Tian et al. (2003). On the basis of TEM 4.2, TEM 4.3 has been developed to include the effects of ozone on plant growth in terrestrial ecosystems (Felzer et al., 2004). In addition, TEM 4.3 includes a new scheme to estimate NPP in agricultural ecosystems. In TEM 4.2, a spatially explicit, empirically derived relative agricultural productivity (RAP) database was used to infer the effects of agricultural practices on crop productivity (McGuire et al., 2001; Tian et al., 2003). Agricultural production was determined by simply multiplying the NPP of the original natural vegetation by a RAP value for the appropriate grid cell. In TEM 4.3, agricultural productivity is no longer dependent on the productivity rates of the original natural vegetation. Instead, the model uses grassland parameterizations to describe the carbon and nitrogen dynamics of crop plants. In this study, we used TEM 4.3 to simulate the effects of cropland expansion and forest regrowth on abandoned cropland on terrestrial ecosystem carbon dynamics in the southern United States. The soil organic matter dynamics of cropland, however, are still based on the parameterizations of the original natural vegetation (Felzer et al., 2004). We did not include ozone effect in this simulation by using zero ozone concentrations across the region.

Annual Gridded Land-Cover Data Sets during 1860–2003

We reconstructed the annual historical gridded land-cover data sets from 1860 to 2003 with a spatial resolution of 8 km (Fig. 1). These data sets were developed based on several data sources, including the global land-cover 2000 (GLC2000) (Bartholomé et al., 2002), the 1992 National Land Cover Data set (NLCD), the global potential vegetation data (Ramankutty and Foley, 1998, 1999), historical cropland county-level data during 1850–1997 from the Census of Agriculture, National Agricultural Statistical Service (http://www.nass.usda.gov/Census_of_Agriculture/index.asp, verified 24 Jan. 2006), and the state-level urban area survey data from the USDA Economic Research Service (http://www.ers.usda.gov/, verified 24 Jan. 2006). The potential vegetation maps for our model run in the southern United States were derived from GLC2000 with a resolution of 1 km (Bartholomé et al., 2002). We reclassified the potential vegetations into 11 vegetation types and replaced the cropland and urban area in the GLC2000 with reclassified potential vegetation types from Ramankutty and Foley (1998, 1999). The nine vegetation types in the southern United States region included temperate coniferous forest, temperate deciduous forest, temperate evergreen broadleaf, mixed temperate forest, Mediterranean-shrublands, dry shrubland, temperate savannas, temperate non-forested wetland, and short-grassland. Water body was excluded in the analysis. Except for cropland and urban and built-up, we assume the nine vegetation types distributed in 2000 are the potential vegetation types distributed before 1860 and changes in cropland and urban are the only major forces to influence the distribution of the nine vegetation types.

We aggregated the 30-m resolution land-cover maps (from 1992 NLCD) into the 8-km resolution, and recorded the area fraction of each land-cover type in each grid. Then, we did temporal interpolation by calculating the cropland for each cell in each year using the cropland census data as the change trends. We used county-level relative change of cropland from the Census of Agriculture as controls to identify change rate of cropland so that the total area of a certain land-cover type would match the county-level data. The annual urban area data set from 1860 to 1997 was developed by the assuming that the urban area was positively correlated with population (Waisanen and Bliss, 2002). During 1945–1997, the state-level urban area survey data (once every 5 yr) conducted by the USDA Economic Research Service (http://www.ers.usda.gov/, verified 24 Jan. 2006) was used as a control to generate the annual urban area data set using the linear interpolation method. We used the potential vegetation map as the natural vegetation map of this region to generate the baseline conditions in the equilibrium portion of the simulations. In TEM simulation, urban area was treated as cropland since a large proportion of urban areas are parks and lawn in the southern United States. In this study, we assume that no conversion among the potential vegetation types, except for the conversion to cropland, occurred during 1860–2003. We also assume that all the vegetation types except cropland were in equilibrium state in 1860.

Other Data Sets

In this study, climate, soil, elevation, and cloudiness are assumed not to vary from year to year. Climatological data sets used by TEM 4.3 in this study include the historical air temperature, historical precipitation, and cloudiness data. The mean monthly temperature and precipitation used the 30-yr average of temperature and precipitation from 1961 to 1990 at 4 km of spatial resolution, which was developed by the Spatial Climate Analysis Service, Oregon State University (ftp://ocs.oce.orst.edu//pub/prism/us/grids, verified 24 Jan. 2006). The elevation data represents an 8-km aggregation of the 7.5-min

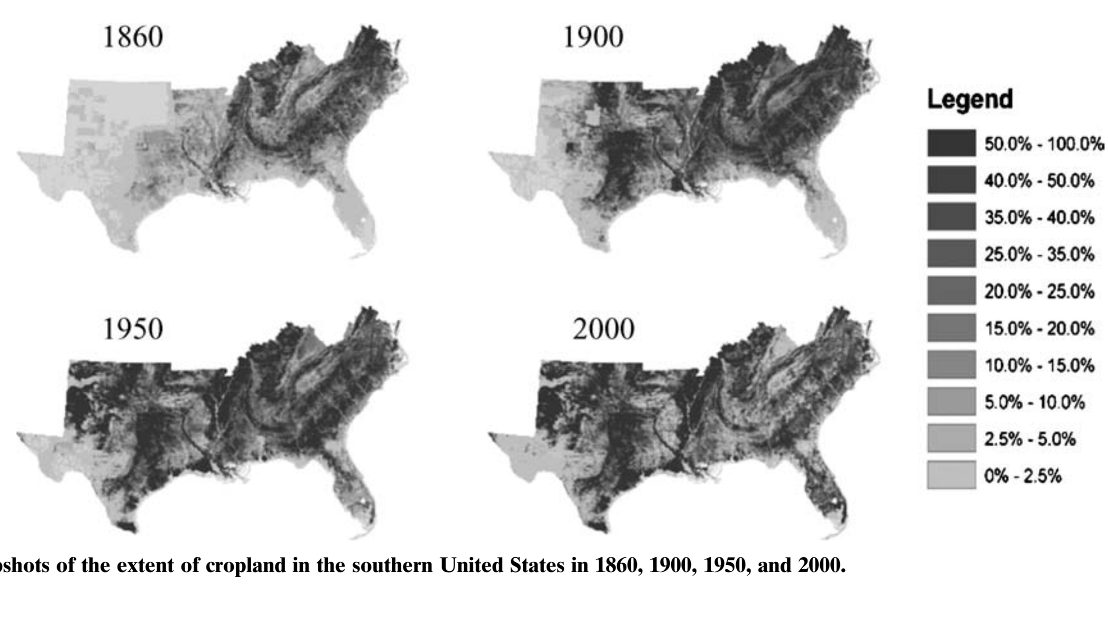

Fig. 1. Snapshots of the extent of cropland in the southern United States in 1860, 1900, 1950, and 2000.

USGS National Elevation Dataset (http://ned.usgs.gov/, verified 24 Jan. 2006). We used the 8-km resolution digital general soil association map (STATSGO map) developed by the National Cooperative Soil Survey to create the soil texture map of the study area. The texture information of each map unit was estimated using the USDA soil texture triangle (Miller and White, 1998). The mean monthly cloudiness data in this study was derived from the Climatic Research Unit (CRU) TS 2.0 climate data-set (T.D. Mitchell et al., unpublished data). The original resolution is 0.5 degree. We constructed the cloudiness map of 8-km resolution in the research area by linear interpolation.

Simulation Approach

To determine the effects of land-cover change alone, we ran TEM 4.3 using the gridded annual land-cover data set only and all other input data sets were constant values. The constant input data sets included the long-term mean monthly climate (30-yr averages of 1961 to 1990) and a constant atmospheric CO_2 concentration (286 ppmv in year 1860). To apply TEM to a transient scenario, it is first necessary to run the model to equilibrium with a long-term baseline climate appropriate to the initial year of the simulation. Then we ran TEM in transient mode using the annual land-cover map from 1860 to 2003 as the input. In the TEM simulation, we ran three times of spin up with 40 yr for each spin. The data used to calibrate the model for different vegetation types is documented in previous work (Raich et al., 1991; McGuire et al., 1992; Tian et al., 1999). Detailed documentation on the development, parameterization, and calibration of the dynamic version of TEM has also been published in a previous work (Tian et al., 1999, 2003).

RESULTS

Land-Cover Change during 1860–2003

Land-Cover Change in the Southeast

The major land-cover types in the SE included forests and cropland (Fig. 2A). Forests covered about 40.7 million ha and 68.3% of the SE land in 1860. In the next 45 yr, the amount of forest land declined by 5.2 million ha. In contrast, the cropland increased from 12.5 million ha and 21% of the SE land in 1860 to 19 million ha and 32% of the SE land around 1910. Since 1910, forest area started to increase and reach about 45 million ha with 75.6% of coverage in 2003. Meanwhile, cropland area decreased over time to reach about 19% of the SE land with a total of 11.5 million ha in 2003. In addition, the urban area increased, especially after 1945, reaching about 6% of the SE land in 2003.

Land-Cover Change in the South-Central

The major land-cover in this subregion included forests, cropland, short-grasslands, and Mediterranean-shrublands (Fig. 2B). Forests covered about 73.6 million ha and 47.1% of the SC land in 1860. During 1860–1940, the amount of forests declined by 15.3 million ha. In contrast, cropland increased from 13.5 million ha and 8.6% of the SC land in 1860 to 58.3 million ha and 37% of the SC land in 1940. In the same period, grasslands lost about 27.4 million ha and kept relatively stable after that period. However, that was not the case for forests and cropland. After 1940, forest area started to increase and reach about 60.8 million ha with a 39% of coverage rate in 2003. Meanwhile, cropland area decreased over time to reach about 30% of the SC land with a total of 46 million ha in 2003. In addition, the urban area increased, especially after 1945, reaching about 2% of the SC land in 2003.

Land-Cover Change in the Entire Southern United States

In the southern United States as a whole, land-cover change varied with types and time during 1860–2003 (Fig. 2C). Forest cover on average declined from 53% in 1860 to 42% in 1940 and showed a steady increase since then to reach 49% in 2003. In contrast, the cropland increased from 12% in 1860 to its peak of 35% in 1940 and decreased gradually to 26% in 2003. Grasslands showed a steady decrease in area during 1860–1930, and leveled off after that. Shrubland decreased slightly during the whole period. The urban area increased over time, and the increase picked up since 1940 to reach 3.2% on average in 2003.

During 1860–1940, net area change of land-cover showed that about 22.7 million ha of forests and 22.6 million ha of grasslands were converted to cropland. In addition, 3 million ha of shrublands and 2.9 million ha of wetlands and savanna were cultivated for crops during the same period (Table 1). The trend was reversed during 1940–2003. About 14.4 million ha of cropland were abandoned and converted to forests, although a small amount of shrubland and wetland and savanna continued to be cultivated (Table 1).

Comparison of Forest Cover Data with Forest Inventory and Analysis Data

We compared the forest cover data in this study to the forest cover data derived from FIA data. The forest coverage rates in 1987 and 1997 were comparable to the FIA forest cover data, although our results usually were higher (Fig. 3). On average, the forest coverage rate in the southern United States was 48% in comparison to FIA's 40% in both 1987 and 1997. For Oklahoma and Texas, our data were very close to the FIA's data. The large differences of our forest coverage rates and FIA's data occurred in Alabama, Florida, and Virginia, and the difference could be up to 16%.

Carbon Storage Change

Change in Carbon Storage in the Southern United States

The carbon storage in terrestrial ecosystems in the southern United States decreased due to land-cover change since 1860 (Table 2 and Fig. 4C). The TEM simulation estimated that total carbon storage in the southern United States in 1860 was 36.8 Pg C, with about 23.3 Pg C in the vegetation and 13.5 Pg C in the reactive soil organic carbon pool. According to the TEM

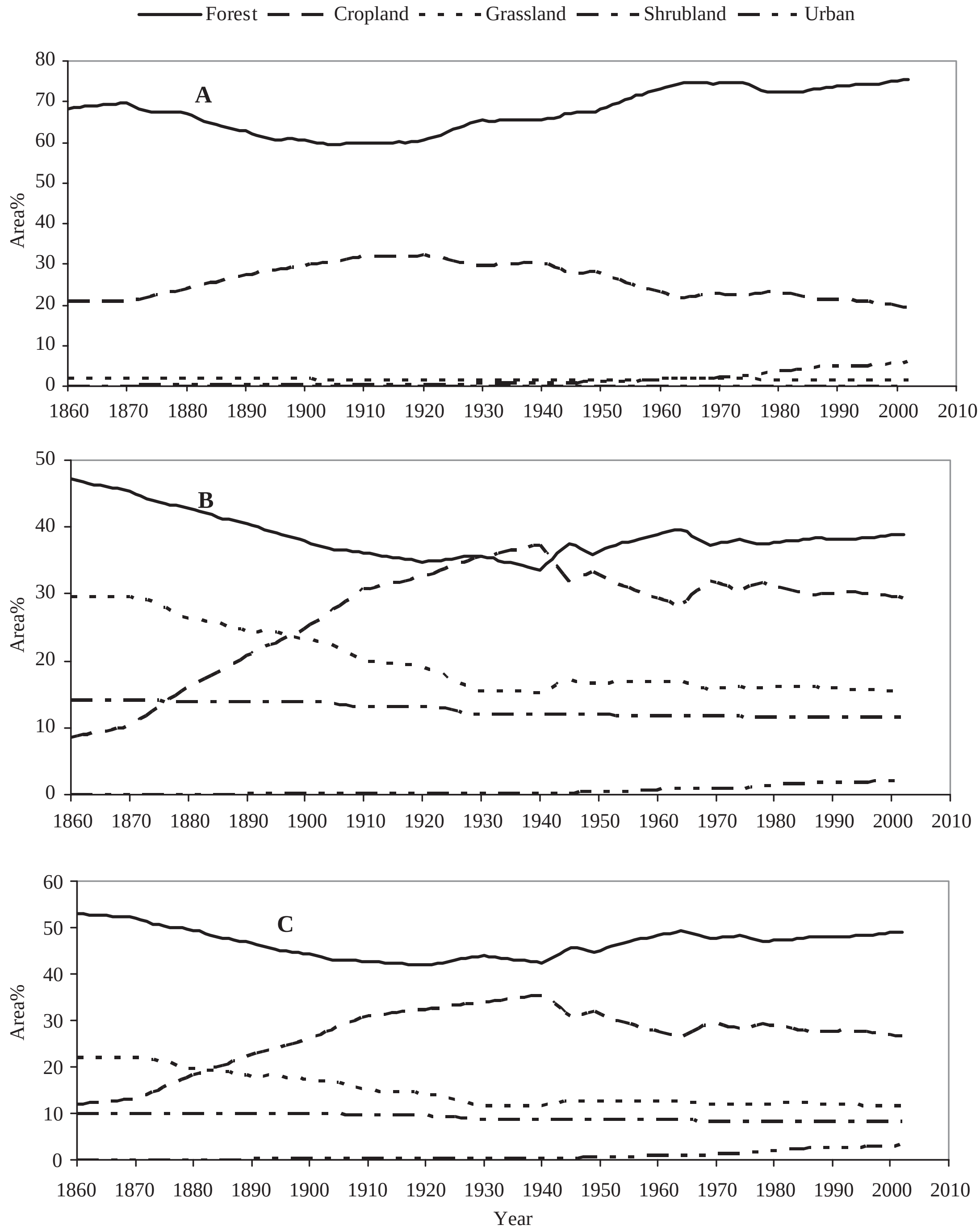

Fig. 2. Land-cover area change in the southern United States during 1860–2003 for the (A) southeast, (B) south-central, and (C) entire southern United States.

simulation, a total of 9.4 Pg C, including 6.5 Pg C of vegetation and 2.9 Pg C of soil C pool, was released into the atmosphere during 1860–2003. The decrease of carbon storage in vegetation and soil primarily occurred during 1860–1940 (Table 2 and Fig. 4C). A total of 9.0 Pg C, including 6.9 Pg C of vegetation and 2.1 Pg C of soil pool in the region, was released into the atmosphere in the period. The total carbon storage did not change appreciably in the southern United States between 1940 and 1980, but did show a slight increase, then a slight decrease (Table 2 and Fig. 4C). Between 1980 and 2003 the total carbon storage declined slightly due to the continued decrease in soil carbon storage, although vegetation carbon was very stable during that time period (Table 2 and Fig. 4C). During 1940–2003, the vegetation carbon storage actually increased by 0.4 Pg, but soil carbon pool continued to release another 0.8 Pg C to the atmosphere in the southern United States region (Table 2).

The total carbon storage in the SE was 10.9 Pg C in 1860 in comparison to 26 Pg C in the SC. According to the TEM simulation, the decrease of total carbon storage in the SE and SC subregions primarily occurred

Table 1. Net area change of land-cover between 1860 and 1940 and between 1940 and 2003.

		Land-cover					
		Forest	Cropland	Grassland	Shrubland	Other	
		million ha					
				1940			Total of 1860
1860	Forest	91.5	22.7	NA†	NA	NA	114.2
	Cropland	0	26.2	0	0	0	26.2
	Grassland	NA	22.6	24.9	NA	NA	47.5
	Shrubland	NA	3.0	NA	18.9	NA	21.9
	Other	NA	2.9	NA	NA	2.9	5.8
Total of 1940		91.5	77.4	24.9	18.9	2.9	215.6
				2003			Total of 1940
1940	Forest	91.5	0	NA	NA	NA	91.5
	Cropland	14.4	62.6	0.4	0	0	77.4
	Grassland	NA	0	24.9	NA	NA	24.9
	Shrubland	NA	1.0	NA	17.9	NA	18.9
	Other	NA	0.7	NA	NA	2.2	2.9
Total of 2003		105.9	64.3	25.3	17.9	2.2	215.6

† Not applicable.

during 1860–1920 and 1860–1940, respectively (Fig. 4A and 4B). The total carbon storage in the SE increased during 1920–1980 while the total carbon storage in the SC increased during 1940–1980. After 1980, the total carbon in both subregions had a slight decrease (Table 2 and Fig. 4A and 4B). However, there were some differences in the change of vegetation carbon and soil carbon in the SE and SC subregions. The carbon storage in vegetation in SE declined rapidly during 1860–1920, then increased during 1920–1980, and declined again since 1980 (Fig. 4A and Table 2). Similarly, the carbon storage in soils declined rapidly during 1860–1920 in the SE. After 1920 there was not an appreciable change in carbon storage in soils in the SE. In the SC, the carbon storage in vegetation and soil pools decreased rapidly during 1860–1940. After 1940, carbon storage in the vegetation pool increased 0.3 Pg while carbon storage in soils continued to decrease but at a much slower rate (Fig. 4B and Table 2).

Change in Carbon Storage in Forests

The largest carbon loss in the southern United States as a whole came from the change in carbon storage of forests (Table 2). According to the TEM simulation, we estimated that total carbon storage in forests was 30.5 Pg C, about 21.9 Pg C in vegetation, and 8.6 Pg C in the reactive soil organic carbon pool in 1860, accounting for 83, 94, and 64% of the total carbon, vegetation carbon, and soil carbon in the region, respectively (Table 2). In this study, the forests include the regrowth forests on abandoned cropland as well as the mature forests. After 144 yr, the total carbon storage, vegetation carbon storage, and soil carbon storage were decreased by 8.2,

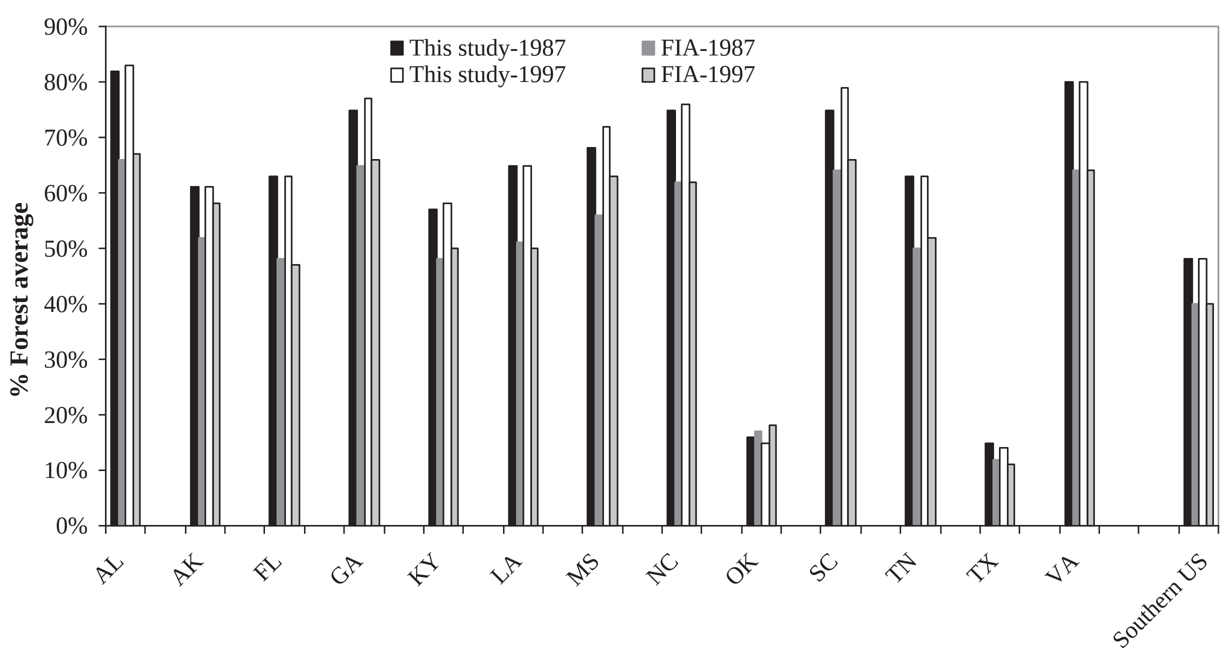

Fig. 3. Comparison of forest coverage between this study and Forest Inventory and Analysis (FIA)–derived data.

Table 2. Change of carbon storage due to land-cover change in the southern United States, forests, and cropland as estimated by the Terrestrial Ecosystem Model (TEM).

Year	Southeast			South-central			Southern		
	VEGC†	SOLC‡	TOTC§	VEGC	SOLC	TOTC	VEGC	SOLC	TOTC
	Pg C								
	Southern United States								
Baseline (1860)	7.3	3.5	10.8	16.0	10.0	26.0	23.3	13.5	36.8
1900	−1.3	−0.2	−1.5	−3.7	−0.5	−4.2	−5.0	−0.7	−5.7
1940	−1.3	−0.6	−1.9	−5.5	−1.5	−7.0	−6.9	−2.1	−9.0
1980	−1.2	−0.7	−1.9	−5.3	−2.1	−7.4	−6.5	−2.8	−9.3
2003	−1.3	−0.7	−2.0	−5.2	−2.2	−7.4	−6.5	−2.9	−9.4
	Forests								
Baseline (1860)	7.1	2.8	9.9	14.8	5.8	20.6	21.9	8.6	30.5
1900	−1.3	−0.5	−1.8	−3.4	−1.3	−4.7	−4.7	−1.8	−6.5
1940	−1.4	−0.6	−2.0	−5.0	−1.9	−6.9	−6.4	−2.5	−8.9
1980	−1.2	−0.5	−1.7	−4.7	−1.9	−6.6	−5.9	−2.4	−8.3
2003	−1.3	−0.5	−1.8	−4.6	−1.8	−6.4	−5.9	−2.3	−8.2
	Cropland								
Baseline (1860)	0.004	0.537	0.541	0.003	0.385	0.388	0.007	0.922	0.929
1900	+0.003	+0.280	+0.283	+0.020	+1.661	+1.681	+0.023	+1.941	+1.964
1940	+0.001	+0.007	+0.008	+0.030	+2.245	+2.275	+0.031	+2.252	+2.283
1980	0.000	−0.145	−0.145	+0.020	+1.523	+1.543	+0.020	+1.378	+1.398
2003	0.000	−0.214	−0.214	+0.016	+1.344	+1.360	+0.016	+1.130	+1.146

† Vegetation carbon.
‡ Reactive soil organic carbon.
§ Total carbon storage.

5.9, and 2.3 Pg C, respectively. These carbon losses accounted for 85, 89, and 77% of the entire regional carbon loss in total carbon, vegetation carbon, and soil carbon, respectively. Most of the carbon loss primarily occurred before 1900 in the SE and before 1940 in the SC. Since 1940 the forest regrowth on abandoned cropland increased carbon storage in the southern United States by as much as 0.7 Pg, including 0.5 and 0.2 Pg C in vegetation and soil, respectively. The carbon sink due to forest regrowth from 1940 to 2003 was 0.1 and 0.4 Pg C in the SE and SC, respectively.

Change in Carbon Storage in Cropland

The total carbon storage in cropland in the southern United States as a whole increased from 0.929 Pg in 1860 to 1.146 Pg C in 2003 (Table 2). The carbon storage in cropland vegetation was much smaller than the carbon storage in soil (Table 2). In the SE, there was no increase in carbon storage in crops, and even a decrease in carbon storage in cropland soil since 1940. However, the carbon storage in crop and soil in the SC continued to increase after 1940, but at lower rates.

Comparison of Carbon Density with Forest Inventory and Analysis–Derived Data

To check the quality of carbon density results of TEM simulation, we compared the average vegetation carbon density and soil density of hardwood in three states with the FIA-derived carbon density (Table 3). The vegetation carbon density of Georgia, Oklahoma, and Virginia in 1987 was 77.3, 42.5, and 106.5 Mg ha^{-1} in comparison to the corresponding FIA data of 63.7 to 67.1, 34.6 to 41.2, and 83 to 97.6 Mg ha^{-1}, respectively. The soil carbon density of the three states was 73.2, 84.3, and 76.6 Mg ha^{-1} in comparison to FIA data of 71.1, 70.8, and 76.1 Mg ha^{-1}, respectively. In addition, we also compared the vegetation carbon and soil density in 1997 with the corresponding FIA data. In general, the TEM simulation results of vegetation carbon density were higher.

Temporal and Spatial Patterns of Regional Net Carbon Exchange

Regional Net Carbon Exchange in the Southern United States

The annual regional NCE had substantial temporal and spatial variations (Table 4). The regional NCE values in 1860, 1900, 1940, 1980, 1990, 2000, and 2003 are listed in Table 4. Most years, the regional NCE values in the southern United States as a whole were negative values. The largest carbon source value in the southeast, south-central, and southern United States was in 1900 with 30.1, 96.2, and 126.3 Tg C yr^{-1}, respectively. In general, the carbon source values were getting smaller over time, although the region was still a carbon source to the atmosphere in 1980, 1990, and 2000.

The average NCE had temporal and spatial variability across the region as well (Fig. 5). From 1860 to 1900, most terrestrial ecosystems in this region released carbon. This pattern was changed during 1901–1950. Some areas, in particular the SE, became a carbon sink. The area of carbon sink continued to expand westward. From 1951 to 2000, most southeast states, except for Florida, and south-central states became a carbon sink.

Regional Net Carbon Exchange of Forests in the Southern United States

Forests had a positive annual NCE value in all the years listed in Table 4. Among the years, the highest regional NCE in the SE was in 1940 with a value of 16.7 Tg C yr^{-1} while the highest regional NCE in the SC was in 1980 with a value of 15.5 Tg C yr^{-1}. For the entire southern United States, the largest regional NCE value

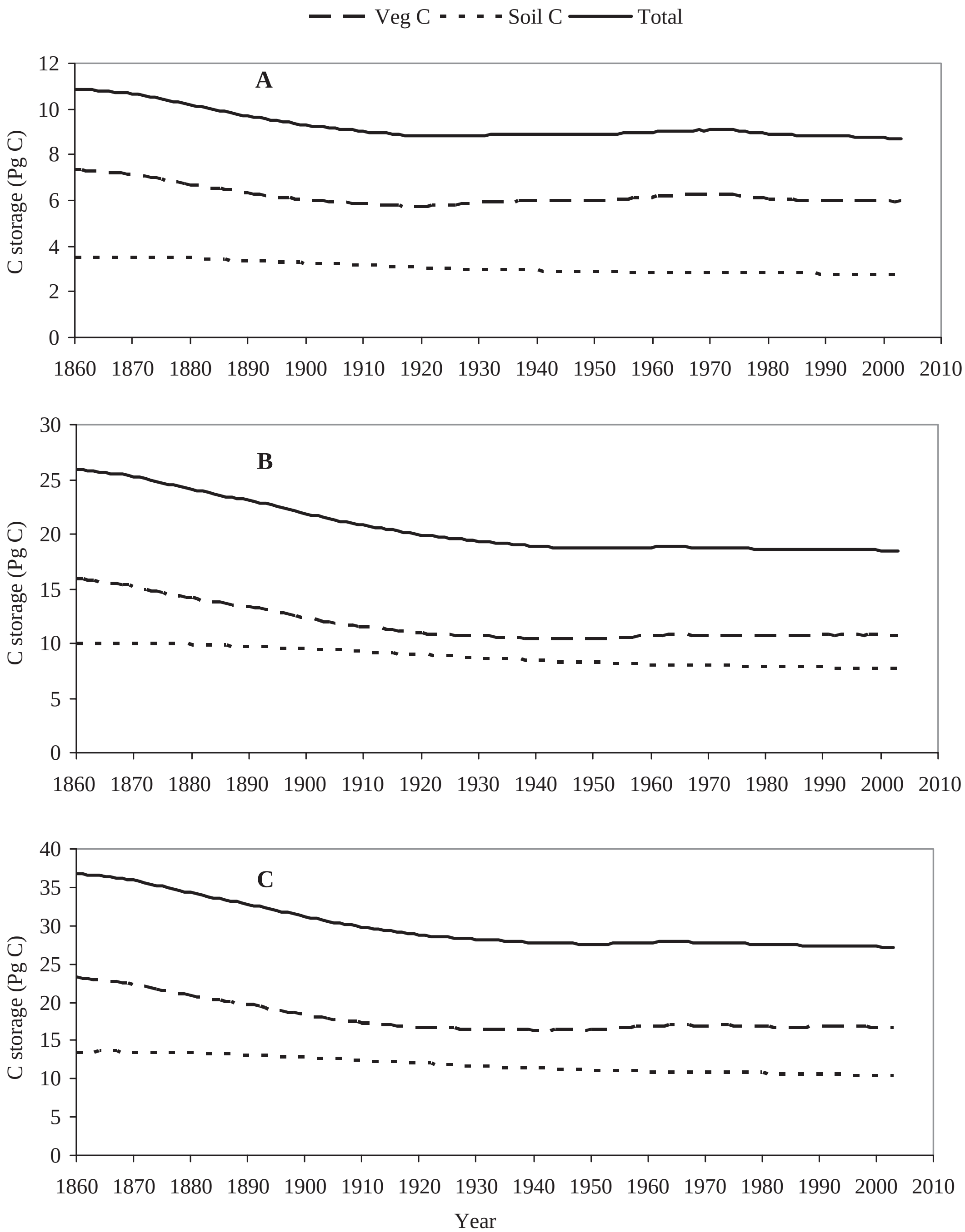

Fig. 4. Change of carbon storage due to land-cover change in the southern United States as estimated by the Terrestrial Ecosystem Model for the (A) southeastern, (B) south-central, and (C) southern United States.

occurred in 1940 with a value of 28.4 Tg C yr^{-1}. Since 1980, the regional NCE of forests declined gradually in SE and SC.

Regional Net Carbon Exchange of Cropland in the Southern United States

Cropland had negative annual NCE during 1860–2003 (Table 4). Among the years listed in the Table 4, cropland released the largest amount of carbon to the atmosphere in 1900, regardless of the subregion. In 1900, the regional NCE value of cropland in the SE, SC, and southern United States was 36.5, 129.9, and 166.4 Tg C yr^{-1}, respectively. The regional NCE of cropland, in general, decreased over time. However, it was relatively stable in 1990, 2000, and 2003.

Regional Carbon Budget during 1860–2003

As a whole, the GPP and NPP values of the southern United States were 330.97 and 172.32 Pg C, respectively, during 1860–2003 (Table 5). In the 144 yr, the regional ecosystem respiration (including autotrophic and heterotrophic respiration) was 324 Pg C, accounting for

Table 3. Comparison of carbon density of forests in the southern United States from Terrestrial Ecosystem Model (TEM) simulation in this study with Forest Inventory and Analysis (FIA)–derived carbon density from other studies.

		Year				
		1987			1997	
		Data source				
Component	State	This study	Birdsey and Lewis (2003)	Brown et al. (2003)†	This study	Birdsey and Lewis (2003)
		Mg ha^{-1}				
Vegetation C	Georgia	77.3	63.7	67.1	78.7	67.9
	Oklahoma	42.5	34.6	41.2	41.2	42.1
	Virginia	106.5	83	97.6	106.5	88.3
Soil C	Georgia	73.2‡	71.1	NA§	74.2‡	70.1
	Oklahoma	84.3‡	70.8	NA	84.6‡	71.8
	Virginia	76.6‡	76.1	NA	77.9‡	72.8

† Data were collected between 1983–1996. The biomass data were converted to carbon density using a constant of 0.5.
‡ Reactive soil organic carbon.
§ Not available.

97% of the GPP. About 4.34 Pg C was released via the burning of slash and fuelwood due to the clearing of natural vegetation for agriculture in the period (Table 5). The C emissions from 1-, 10-, and 100-yr products were 9.37, 2.04, and 0.56 Pg, respectively, in the entire period. During 1860–2003, the southern United States released a total of 9.4 Pg carbon into the atmosphere.

During 1860–2003, the GPP and NPP in the SE were 94.16 and 46.95 Pg C and in the SC were 236.81 and 125.37 Pg C, respectively. About 98.2 and 97.8% of GPP was consumed by ecosystem respiration in the SE and SC during the 144 yr, respectively. In total, about 2.48 and 9.48 Pg C was released from the products composed by various residence times in the SE and SC subregions, respectively. The SE contributed about 22% while the SC contributed the other 78% of the total net carbon source of 9.4 Pg C in 144 yr.

DISCUSSION

Land-Cover Change

Our study indicated that the southern United States region experienced a long-term transition from forests to agricultural land use, and then to secondary forests during 1860–2003. In this transition, the pattern of land-cover change in the southern United States was primarily driven by the change of cropland. This could be explained using the three primary waves of land-use change that occurred in the 144-yr period in the southern United States. The first wave of land-use change was cropland expansion moving from the east to the west (Fig. 1). New cropland was established by conversion from natural vegetation between 1860 and 1910 in the SE and between 1860 and 1940 in the SC (Fig. 2A and 2B). History of land clearing for cropland in this region could trace back much earlier. Agricultural exploitation started in the 17th century but reached its zenith in the late 19th century, when a vast cotton industry stretched from the Atlantic coast to Texas (Wear, 2002). The second wave of land-use change was characterized by forest regrowth on abandoned cropland. This wave of change also moved from the east to the west. Forest area increased about 10 million ha in the SE between 1910 and 2003. Similarly, forest area increased about 8 million ha in the SC between 1940 and 2003. The magnitude of this wave of land-use change was much smaller than the first wave of cropland expansion, especially in the SC (Fig. 2B). The land-use pattern has experienced relatively stability since 1940. During the past 144 yr, total cropland only declined by 1 million ha and the total forest area increased by less than 5 million ha in the SE. However, total cropland area actually increased by about 33 million ha, and total of forest area declined by 13 million ha in the SC. Urbanization is the most recent wave of land-use change. Urban area increased rapidly since 1940 (Fig. 2), especially in the SE. The urban area in the southern United States increased by more than six times to reach 3.5 million ha more in 2003 than in 1941.

The land-cover pattern observed in this study was consistent with the few available studies (Wear, 2002). Wear (2002) found most states in the southern United

Table 4. Change of net carbon exchange (NCE) in the southern United States, forests, and cropland between 1860 and 2003 as estimated by the Terrestrial Ecosystem Model (TEM).

Year	Southeast	South-central	Southern
	Tg C yr^{-1}		
	Southern United States		
Baseline (1860)	−2.4	−2.0	−4.4
1900	−30.1	−96.2	−126.3
1940	+3.8	−45.2	−41.4
1980	−16.0	−7.4	−23.4
1990	−4.9	−7.6	−12.5
2000	−10.9	−11.6	−22.5
2003	−3.4	−7.6	−11.0
	Forests		
Baseline (1860)	+0.1	+0.2	+0.3
1900	+4.7	+1.2	+5.9
1940	+16.7	+11.7	+28.4
1980	+7.2	+15.5	+22.7
1990	+5.7	+12.5	+18.2
2000	+6.4	+8.8	+15.2
2003	+7.2	+9.4	+16.6
	Cropland		
Baseline (1860)	−2.5	−2.2	−4.7
1900	−36.5	−129.9	−166.4
1940	−15.3	−67.5	−82.8
1980	−25.6	−27.5	−53.0
1990	−10.7	−21.4	−32.1
2000	−20.6	−21.9	−42.5
2003	−10.7	−18.8	−29.5

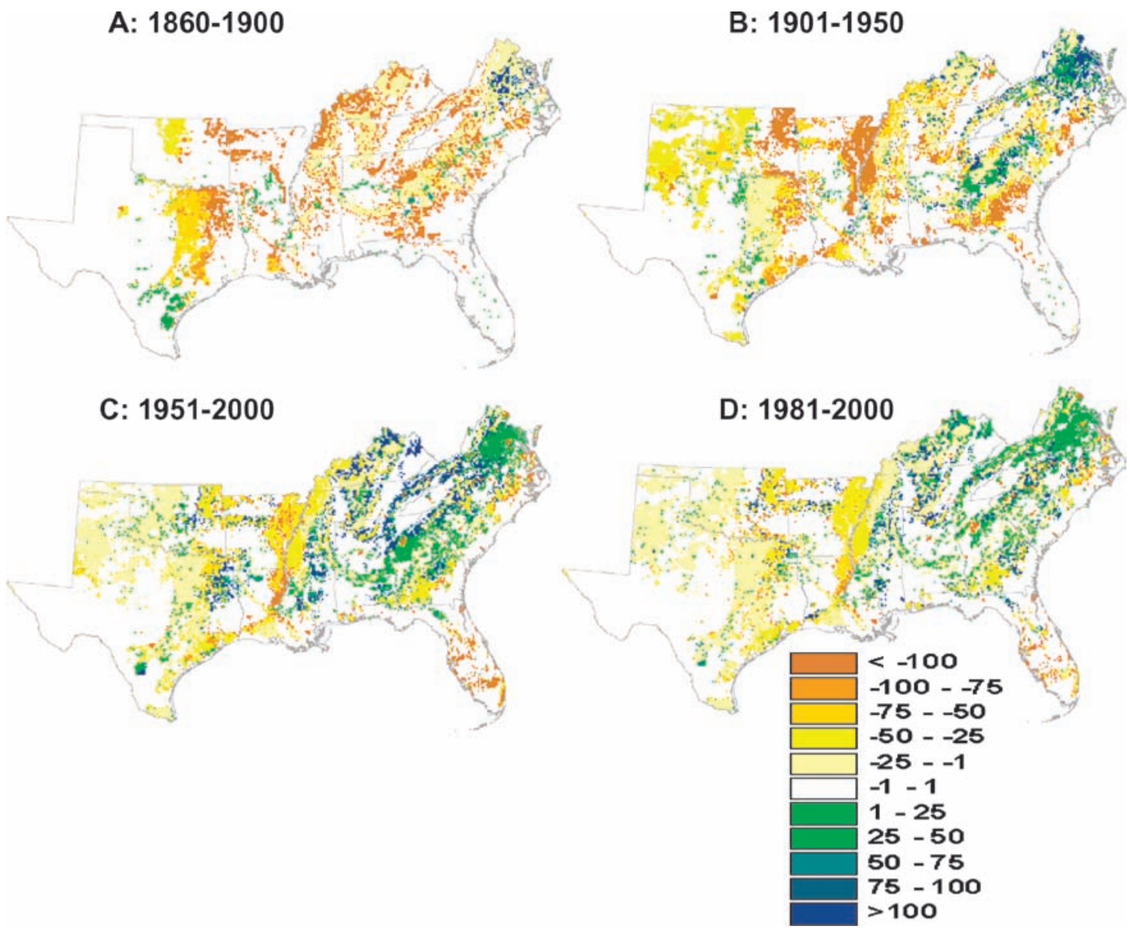

Fig. 5. Average annual net carbon exchange (NCE) caused by land-cover change in the southern United States (g C m^{-2} yr^{-1}) for (A) 1860–1900, (B) 1901–1950, (C) 1951–2000, and (D) 1981–2000.

States experienced relatively stable land-cover distribution between 1945 and 1992. Stable forest area or cropland, however, does not mean that there has been no change in the character of the forest or cropland. There have been shifts from agriculture to forests and vice versa. The higher forest cover in our study than in the FIA-derived forest cover data could be attributed to several factors. The annual forest cover in this study was derived from the global land-cover 2000 and annual cropland distribution. The global land-cover 2000 was developed from Landsat TM with a spatial resolution of 30 m. Thus, the forest cover data here included forest cover in urban areas such as city parks, while the FIA forest cover data did not. Moreover, minimum area considered for classification in FIA is 0.4047 ha, larger than the minimum area considered by the global land-cover 2000. All these differences could cause the forest cover in this study to be higher than the corresponding FIA-derived data.

Change in Regional Carbon Storage

Our study indicates that land-cover change has significant influence on carbon dynamics in the southern United States. The conversion of natural forests to cropland can release substantial amounts of carbon to the atmosphere through the loss of carbon from both vegetation and soils. During 1860–2003, terrestrial ecosystems in the southern United States acted as a source of carbon to the atmosphere (Table 2). According to the TEM simulation, the regional carbon storage decreased from 36.8 Pg C in 1860 to 27.4 Pg C in 2003, resulting from the land-cover change. Most of the 9.4 Pg C decrease in storage occurred in the SC subregion, while the

Table 5. Contribution of land-cover change to regional carbon budget during 1860 to 2003.

Term†	Southeast	South-central	Southern
		Pg C	
GPP	94.16	236.81	330.97
R_A	47.21	111.44	158.65
NPP	46.95	125.37	172.32
R_H	45.27	120.14	165.41
E_{AD} (conversion flux)	1.29	3.05	4.34
Ep			
Decay from 1-yr product (e.g., agricultural products)	1.70	7.67	9.37
Decay from 10-yr product (e.g., paper and paper products)	0.63	1.41	2.04
Decay from 100-yr product (e.g., lumber and long-lasting products)	0.16	0.40	0.56
NCE = NPP − R_H − E_{AD} − Ep	−2.1	−7.3	−9.4

† GPP, gross primary production; R_A, autotrophic respiration; NPP, net primary production; R_H, heterotrophic respiration; E_{AD}, emissions from anthropogenic disturbance such as cropland conversion from forests; Ep, decomposition of products harvested from ecosystems for use by humans and associated livestock; NCE, net carbon exchange.

SE only lost 2.1 Pg C in the 144 yr. This pattern was primarily due to the high proportion of cropland in the SC (Fig. 2B). In 2003, cropland in the subregion was 30% of the land with 46 million ha, three times more than the cropland area in 1860. In contrast, cropland in the SE was only 19% of the land in 2002 with 11.5 million ha, smaller than the amount of cropland in 1860 in the subregion. In addition to the spatial variation, the changes in carbon storage also varied temporally. In the SE, the carbon storage did not change appreciably since 1940 while the carbon storage in the SC did not change since 1980.

The initial regional carbon storage of 36.8 Pg C in 1860 (Table 2) was probably overestimated due to the model assumption. This was also reflected by the higher carbon density in this study than in the FIA-derived data (Table 3). In the model simulation, we assume all the vegetation types were mature and in equilibrium state except cropland in 1860. This assumption is unlikely to be true given the history of land clearing for cropland could trace back much earlier than 1860 in this region (Wear, 2002). Thus, forest regrowth on abandoned cropland could occur before 1860, suggesting that some forests in 1860 were secondary forests instead of mature forests. As the carbon storage in secondary forests was lower than mature forests (Birdsey and Lewis, 2003), the model estimate of carbon storage in 1860 was likely overestimated. As agricultural exploitation started in the 17th century in this region (Wear, 2002; Smith and Darr, 2005) it is necessary to develop longer-term historical land-cover data sets than 144 yr to make a better estimate of the historical carbon storage dynamics in this region.

Independent studies, in which the total net flux of carbon (change in total carbon storage) was estimated using a bookkeeping model (Houghton and Hackler, 2000a, 2000b) and FIA data (Birdsey and Heath 1995; Birdsey and Lewis, 2003; Turner et al., 1995), could be used for the result comparisons. Houghton and Hackler (2000a, 2000b) used a bookkeeping model to examine the effects of land-cover change on terrestrial carbon storage in the United States during 1700–1990. They estimated the total flux for the 290-yr period was a release of 32.6 Pg C. About 8.5 Pg C was released from the southern United States region during 1860–1990 based on the graph estimation, which was very close to our estimation (9.4 Pg C). Although we did not consider possible changes in harvest within managed forests as Houghton and Hackler (2000a) did, however, the clearing for cropland with subsequent cultivation and forest regrowth in abandoned cropland was the major source of carbon to the atmosphere, accounting for more than 83% of the long-term total flux (Houghton and Hackler, 2000a). Moreover, emissions of carbon associated with the harvest of industrial wood, including the storage of carbon in products and their oxidation, were general small. The carbon release from 10- and 100-yr product in this study, on average, was only 4.4 and 1.1 Tg yr^{-1}, respectively.

The carbon sink resulting from forest regrowth on abandoned cropland in this study was smaller than the results derived from FIA data (Birdsey and Heath, 1995; Turner et al., 1995). Turner et al. (1995) used FIA data to estimate a net carbon sink for the SE and SC subregion of 74 and 75 Tg yr^{-1} in the 1980s, respectively. Our results indicated that the carbon sink of forests in these two subregions was 5.9 and 14.6 Tg yr^{-1}, respectively. Birdsey and Heath (1995) estimated a carbon sink of 260 Tg yr^{-1} on average over the period 1952–1992. The TEM simulation indicated that the carbon sink of forest regrowth in the SE and SC was 12.9 and 22.1 Tg yr^{-1} for the same time period, respectively. As the FIA-derived carbon sink is almost always 10-fold higher than ours, we believe that the carbon accumulation in forest regrowth on abandoned cropland may have been underestimated in this study. This was further confirmed by the stable total carbon storage in the southern United States even after 1940 when net forest area increased due to cropland abandonment (Fig. 6). This underestimation of carbon accumulation may have something to do with the TEM model. TEM was originally developed to simulate natural ecosystems (Raich et al., 1991; Melillo et al., 1993). Although TEM is later modified to simulate the transitional processes such as land-cover change on carbon dynamics (McGuire et al., 2001; Tian et al., 2003), the model algorithms and calibrated parameters are based on mature terrestrial ecosystems instead of young forests. New sets of calibration of young forests may be needed for the TEM to better simulate the carbon accumulation in regrowing forests on abandoned cropland.

Temporal and Spatial Variability of Net Carbon Exchange

The temporal and spatial variability of annual net carbon exchange is strongly influenced by clearing for cultivation and forest regrowth on abandoned cropland (Houghton et al., 1999; Cairns et al., 2000; Tian et al., 2003). Houghton et al. (1999) found that these two land-use changes were responsible for more than 68% of the net land-use change flux, while harvest of wood, conversion of forests to pastures, and shifting cultivation accounted for 16, 13, and 4% of the net flux, respectively. Tian et al. (2003) indicated that cropland establishment and abandonment during 1860–1990 was responsible for most of the carbon losses in monsoon Asia. The conversion of closed forests to agricultural land caused a loss of approximately 85% of the terrestrial carbon storage in tropical Mexico (Cairns et al., 2000). A meta data review by Murty et al. (2002) indicated that conversion of forest to cultivated land led to an average loss of approximately 30% of soil carbon. Similarly, Guo and Gifford (2002) found that soil carbon declined 42 and 59% after land-use change from native forest, grassland to cropland, respectively.

The magnitude of the land-use change on annual net carbon exchange is highly related to the land-cover change, especially the amount and distribution of cropland (Fig. 1 and 4). In the southern United States, cropland expanded westward (Fig. 1). The average annual NCE map followed a similar pattern by indicating that more carbon was released in the areas with a high proportion of cropland distribution (Fig. 1 and 5). For

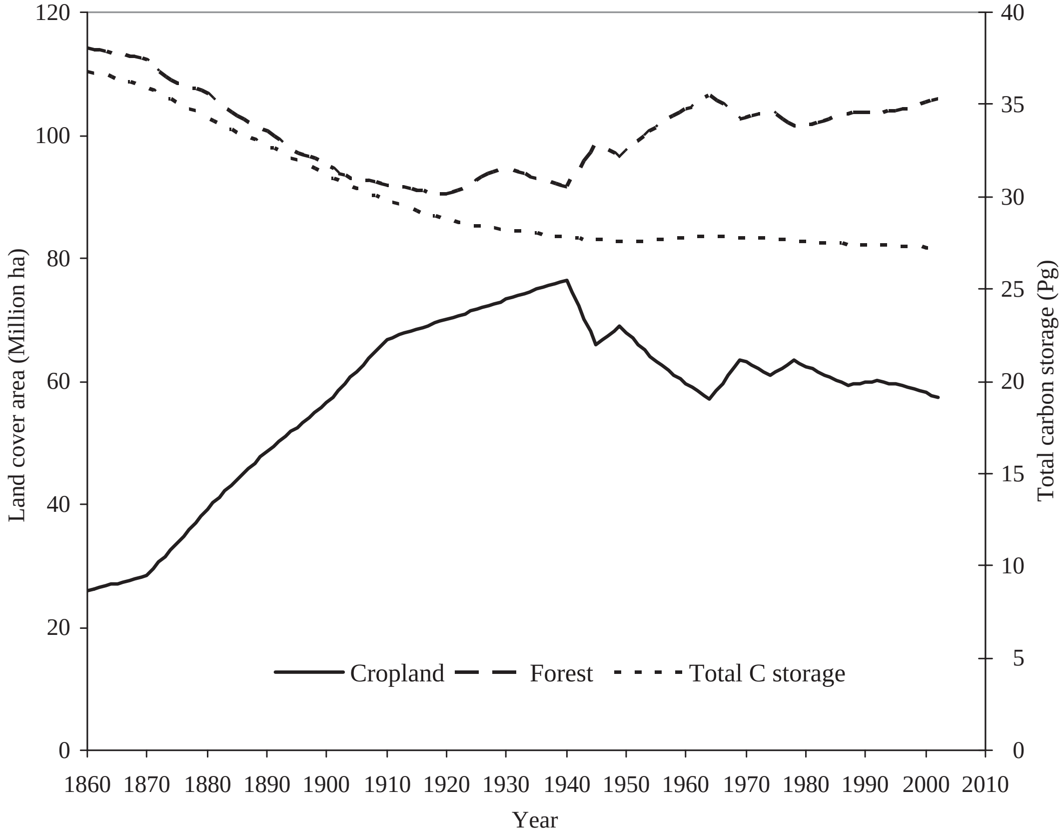

Fig. 6. Relationship between total carbon storage and area of forest and cropland.

example, cropland was widely distributed prevalent in eastern Arkansas, bordering with Tennessee and Mississippi, during 1900–1950 (Fig. 1). This was reflected by the negative NCE values in this area in the average NCE map (Fig. 5B). The close relationship between cropland and average NCE was further confirmed by the NCE pattern of the SE (Fig. 5). Because the cropland expansion from natural vegetations was most rapid around 1880, the NCE in this subregion showed the highest carbon loss then. The forest regrowth wave started to move westward after cropland reached the peak. This could explain why the SE became a carbon sink after 1920 (Fig. 5C and 5D). The close relationship between the cropland dynamics and regional NCE could be also observed from the SC or the entire southern United States. Our study has shown that the spatial distribution of past and current land-cover change is critical for understanding the spatial and temporary variability of NCE over a region. The high resolution annual land-cover data sets from 1860 to 2003 developed in this study have demonstrated the usefulness of examining the spatial and temporary variability of NCE resulting from land-cover change in a region.

Limitations, Improvements, and Future Research Needs

The TEM simulation estimate of changes in carbon storage and flux resulting from land-use change only considers three key processes: (i) conversion from natural vegetation (e.g., forests, grassland) to cropland, (ii) production and harvest on cultivated land, and (iii) forest regrowth on abandoned cropland (Tian et al., 2003). Although these processes were primarily responsible for the carbon lost as a result of land-use change (Houghton et al., 1999; Tian et al., 2003), it is necessary to recognize that the land-use analysis presented here is incomplete and preliminary. Several land-use change processes have not been considered. For example, we did not consider the impact of conversion of other vegetations, such as forests, to pastures or vice versa. We also did not consider possible changes in harvest and regrowth cycles within managed forests. In particular, the timber production on forest plantations is very important in the southern United States. In recent decades, there has been a decided shift in timber productions from the west to the east. The southern region now produces over 50% of commercial timber harvests for the nation (Mickler et al., 2002). Most of the timber harvests occur in forest plantations, which have adopted intensive forest management practices, including site preparation, utilization of pesticides and fertilization, and short-term rotation (Siry, 2002). However, how harvest of wood on these intensively managed plantations influences carbon dynamics in the southern United States remains unclear. As a plantation may be established for timber, shelter belts, orchards, or fuelwood, the storages of carbon in biomass consequently vary. Whether plantations are established on nonforest lands or on recently cleared forests also affects the net changes in biomass and soil carbon that result (Houghton and Goodale, 2004). Houghton et al. (1999) indicated that harvest of wood alone was responsible for 16% of the net land-use flux on average after studying a global level land-use change. Clearly, this is an important land-use process which deserves more attention. Better spatial and temporary data sets of timber harvest and plantation establishment are needed to assess the exact impact of harvest of wood and plantation on carbon dynamics. These data sets should include better spatial and temporary information such as locations of timber harvest and plantations, harvested timber volume, plantation area, type of forest product, and change over time.

Urbanization is another important land-use change in the southern United States (Wear, 2002). The recent U.S. Forest Service Southern Forest Resource Assessment recognized that increased urbanization may represent the most important threat to the southern United States forest land over the next 20 yr (Wear, 2002). The urban area has increased more than eightfold since 1940 in the SE and SC. Conversion of forests into urban buildup could release a tremendous amount of carbon into the atmosphere (Milesi et al., 2003). In this study, we simply consider urban area as cropland in TEM simulation. This simplification provides us a first look. In the future, it is necessary to separate urban from cropland to examine the exact effects of urbanization on carbon dynamics.

Other than land clearing for cropland and urban development, no land-use change is more common in southern forests than fire (Stanturf et al., 2002). Fire could directly influence how much carbon is stored in trees or dead wood (Dale et al., 2001). Repeated fires could reduce the average biomass of forests (Houghton and Hackler, 2000b). Moreover, fire exclusion in the United States is estimated to have been responsible for a cumulative net sink of 8 to 13 Pg C over the period 1850–1990 and 0.05 Pg C yr^{-1} during the 1990s (Houghton and Goodale, 2004). Furthermore, use of prescribed fire is an important forest management activity in the southeastern United States (approximately 2 million ha burned per year) by reducing hardwood and herbaceous competition in young stands, improving wildlife habitat, and minimizing catastrophic wildfire (Mickler et al., 2002). Fire is also used to remove logging slash before plantation establishment. To determine the exact spatial and temporary effects of fire on carbon dynamics in the southern United States, better spatial and temporary data sets are needed, including what and how much vegetation is killed, and thus how much carbon is released in the years following a fire. Houghton and Hackler (2000b) indicated that adding fire and fire management to an analysis of land-use change reduced the emissions of carbon over the period 1700–1990 by 25% (8 Pg C) in the United States. As the area burned annually in the southern United States is traditionally almost 70% of the total area burned in the entire United States (Birdsey, personal communications) the analysis of land-use change including fire and fire management on carbon dynamics in the southern United States could reduce the carbon loss resulting from the land-use change.

Land clearing for cropland, cultivation, and forest regrowth on abandoned cropland have significant impact on regional carbon dynamics (Houghton et al., 1999; Houghton and Hackler, 2000a, 2000b; Tian et al., 1999, 2003). Several key land-use processes such as wood harvest on forest plantations, urbanization, fire, and fire management need to be included in future research to better reflect the effects of land-use change on the spatial and temporary variability of carbon dynamics in the southern United States. In addition, longer-term historical land-cover data sets before 1860 need to be reconstructed to better reflect the land-use change history in this region. Finally, new sets of calibration of young forests may be needed for the TEM model to better simulate the carbon accumulation in regrowing forests on abandoned cropland.

CONCLUSIONS

During 1860–2003, the pattern of land-cover change in the southern United States was primarily driven by the change of cropland. Three waves of land-use change occurred in the 144-yr time period in the southern United States. The first wave of land-use change was cropland expansion from natural vegetation during 1860–1910 in the southeast and 1860–1940 in the south-central. The second wave of land-use change was characterized by forest regrowth on abandoned cropland, moving from the east to the west as well. Forest area increased about 10 and 8 million ha in the southeast (during 1910–2003) and south-central (during 1940–2003), respectively. Urbanization is the most recent wave of land-use change. Urban area increased rapidly since 1940, especially in the SE.

Land-cover change has significant influence on carbon storage and fluxes in terrestrial ecosystems. The TEM simulation estimated that total carbon storage in the southern United States in 1860 was 36.8 Pg C, which likely was overestimated, including 10.8 Pg C in the southeast and 26 Pg C in the south-central. During 1860–2003, a total of 9.4 Pg C, including 6.5 Pg C of vegetation and 2.9 Pg C of soil C pool, was released to the atmosphere in the southern United States, suggesting this region on average acted as a carbon source due to the land-use change. The net carbon flux was approximately zero in the entire southern region between 1980 and 2003. The temporal and spatial variability of annual net carbon exchange is strongly influenced by land-cover pattern, especially the amount and distribution of cropland. A huge amount of carbon was released via the clearing of land for agriculture (e.g., burning of slash and fuelwood) and 1-yr agricultural product. The carbon loss from 10- and 100-yr production pools was much smaller.

We recognize that the land-use analysis in this study is incomplete and preliminary. Several key land-use processes such as wood harvest on forest plantations, urbanization, fire, and fire management need to be included in future research to better reflect the effects of land-use change on the spatial and temporary variability of carbon dynamics in the southern United States. In addition, longer-term historical land-cover data sets before 1860 need to be reconstructed to better reflect the land-use change history in this region. Finally, we also suggest that new calibration sets for the TEM model need to be developed to better simulate forest regrowth on abandoned cropland in the southern United States.

ACKNOWLEDGMENTS

This study has been supported by the Auburn University Peak of Excellence Program, EPA 2004-STAR-L1 Program, Alabama Agricultural Experiment Station Foundation Grant Program, and McIntire-Stennis Program. We thank Christopher Daly at Oregon State University for allowing us to use the high resolution climate data sets (1890–2004) for the southern United States developed by the Spatial Climate Analysis Service, Oregon State University. We would also like to acknowledge the helpful advice of D.W. Kicklighter.

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